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A Statistical Characterization of Shadowed Device-to-Device Communications in an Indoor Environment

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Abstract—This paper presents the results of a measurement campaign aimed at characterizing and modeling the indoor radio channel between two hypothetical cellular handsets. The device-to-device channel measurements were made at 868 MHz and investigated a number of different everyday scenarios such as the devices being held at the user's heads, placed in a pocket and one of the devices placed on a desktop. The recently proposed shadowed κ - μ fading model was used to characterize these channels and was shown to provide a good description of the measured data. It was also evident from the experiments, that the device-to-device communications channel is susceptible to shadowing caused by the human body.

Index Terms—Device-to-device communications, channel measurements, channel modeling.

I. INTRODUCTION

The use of device-to-device (D2D) communications to supplement traditional cellular communications [1-4] will provide an exciting opportunity to provide higher data rates and extend the coverage of cellular networks. This will be achieved by using network users themselves as ad hoc base stations to facilitate the routing of data traffic and to relay broadcasts. An architecture for D2D communications to be used as an underlay for a Long Term Evolution (LTE) Advanced networks has been proposed in [1]. The authors have shown that by using dedicated signaling for session setup and the automatic handover of network routed traffic to D2D links, even for the worst case scenario of interference limited D2D communications an increase in the total throughput in a local cell area can be achieved.

At present, very little is about the characteristics of the D2D communications channel. Compared to conventional cellular communications, where the base station is fixed and typically free of local scattering, in D2D channels, both the transmitter and receiver are in close proximity to the human body (e.g. in a pocket or held), often in motion and at relatively low elevation. Because of this D2D channels will be heavily susceptible to stochastic shadowing events caused by the direct link between a pair of user equipment (UE) being intersected by the user's bodies and also obstacles in the local environment such as vehicles and buildings (outdoors), internal walls and furniture (indoors) and other pedestrians (both indoors and outdoors).

In this paper, the shadowed κ - μ fading model [5] is used to model the received signal for a number of hypothetical D2D links operating in an indoor environment at 868 MHz. The shadowed κ - μ fading model is an extension of the highly versatile κ - μ fading model originally derived by Yacoub [6]. In the κ - μ fading model clusters of multipath waves are

assumed to have scattered waves with identical powers, alongside the presence of elective dominant signal components. The κ - μ distribution itself is an extremely versatile fading model which contains as special cases other important distributions such as the One-Sided Gaussian, Rice (Nakagami- n), Nakagami- m and Rayleigh distributions. While the shadowed κ - μ fading model inherits all of this generality, the critical difference between this model and that of standard κ - μ fading is that the resultant dominant component, formed by phasor addition of the individual dominant components is assumed to be random. In particular it is assumed that this resultant dominant component follows a Nakagami- m distribution.

The remainder of this paper is organized as follows. Section II describes the experimental setup and the D2D channel measurements. The probability density function of the shadowed κ - μ fading model is presented in Section III and used to model the measured channel data. Parameter estimates for log-distance path loss models abstracted from the data are also presented in Section III so that the results presented here can be reproduced. Finally, Section IV finishes the paper with some concluding remarks.

II. EXPERIMENTAL SETUP AND MEASUREMENTS

A. Experimental Setup

The D2D links considered in this study were formed using two Nearson S331AM-868 electrically short monopole antennas which were housed in a compact acrylonitrile butadiene styrene (ABS) enclosure (107 x 55 x 20 mm), herein denoted UE₁ and UE₂. This setup was representative of the form factor of a smart phone which allowed the user to hold the device as they normally would to make a voice call. It also allowed the user to carry the device in the pockets of their clothing. Each antenna was securely fixed to the inside of the enclosure in the position using a small strip of Velcro®. The antennas were connected using low-loss coaxial cables to a Texas Instruments CC1110F32 system on chip which featured a CC1101 transceiver. The CC1110 was chosen for a number of reasons. Firstly, it operated within the European 868 MHz ISM band which is close to the 800 MHz LTE operating frequencies used in various parts of the Americas, Asia, Europe and Middle East and also the 850 band used in the US for GSM, IS-95 and 3G any of which could be used for future D2D communications. Secondly it offered straightforward programming of the radio registers and the ability to readily obtain the received signal strength.

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B. Measurements

The results presented in this paper were obtained from experiments performed in a large, ground floor, L-shaped, open plan living area formed by the intersection of two rooms (room 1, 8.44 m x 3.75 m and room 2, 5.75 m x 4.15 m) which were situated within a two storey residential building. The construction was typical of that encountered in the United Kingdom for this type of dwelling, with a brick and concrete block cavity wall structure. Both the internal walls and ceiling, which was at a height of 2.40 m, were finished with gypsum board and plaster. The floor consisted of porcelain tiles and there were a small number of soft furnishings throughout consisting mainly of wood.

In this study, three types of D2D links were investigated. The first scenario considered a male of height 1.83 m and mass 94.7 Kg (person 1) with UE₁ held at their right ear at a 45 degree angle to the vertical, walking towards and then away from UE₂ which was placed on a desktop. UE₁ was held at an elevation of 1.65 m while UE₂, positioned on the desktop, was at a height of 0.8 m. The second scenario considered person 1 with UE₁ again held at their right ear walking towards and then away from a second person (person 2) who held UE₂ at their right ear. Person 2 was a female of height 1.57 m and mass 51.4 Kg. UE₂ was also held at an angle of 45 degrees to the vertical with an elevation of 1.42 m from ground level. The third scenario considered the case where UE₁ was again held at person 1's right ear except in this instance UE₂ was positioned in person 2's front right jacket pocket, at a height of 0.85 m. It should be noted that for all of the scenarios in which person 1 walked towards UE₂, they did so in a straight line from a distance 5 m away to a position 1 m immediately in front of UE₂ and vice versa when walking away from UE₂. Furthermore, for all measurements involving person 2 with UE₂, person 2 was stationary.

The hypothetical smart phone used by person 1 (i.e. UE₁) was configured to operate at 868.3 MHz using a data rate of 500 kBaud with an output power of 0 dBm. It was programmed to continuously transmit packets with a period of 70 ms to UE₂. UE₂ was configured with a receive filter bandwidth of 812.5 kHz and set to record the packet reception time, sequence number and the received signal strength, which was stored for post-processing on a Dell XPS13 Ultrabook, which featured an Intel i5-2467M processor, 4 GB of RAM and a 128 GB SSD.

III. RESULTS

The shadowed κ - μ fading model [5] was used to statistically characterize the D2D channels considered in this study. The probability density function (PDF) for the received signal in this model is given in equation (1), where κ is related

to δ , σ and μ through the relationship $\kappa = \delta^2 / 2\mu\sigma^2$ which is simply ratio of the total power of the dominant components (δ^2) to the total power of the scattered waves ($2\mu\sigma^2$) where μ is related to the multipath clustering and the mean power is given by \hat{r}^2 . In (1), $\Gamma(\cdot)$ is the gamma function, $m = E^2[\Delta^2] / \text{var}[\Delta^2]$ is the Nakagami parameter where $\text{var}[\Delta^2]$ is the variance [7]. In this instance, $\Omega = E[\Delta^2]$ is the average power of the resultant dominant component.

As discussed earlier, the first set of measurements considered a D2D link in which UE₂ was placed on a desk positioned within the overlapping area of the two rooms. It should be noted that UE₂ was positioned so that it had an orientation similar to a cellular handset placed with its 'back-plate' in contact with the table surface. Person 1 then walked slowly ($\sim 0.5 \text{ ms}^{-1}$), directly towards UE₂ from a distance 5 m away to a point 1 m directly in front of UE₂. Fig. 1 shows the received signal power while person 1 walked towards UE₂. Also shown is the estimated log-distance path loss which was obtained using linear regression.

To prepare the measured data for model fitting, the path loss was removed before transforming the measurements to linear amplitude. All parameter estimates for the shadowed κ - μ fading PDF were obtained using a non-linear optimization algorithm in MATLAB. The estimated parameters for each of channels considered in this study are presented in Table I. Fig. 2 shows the PDF of (1) compared to empirical probability density for the UE₁ head to UE₂ desktop channel while person 1 towards UE₂, also shown for comparison is the κ - μ PDF of [6]. As we can see, for this type of channel, the shadowed κ - μ PDF provides an enhanced fit to the data.

When person 1 was walking towards UE₂ which was positioned on the desktop, the direct link between the two hypothetical UEs is heavily shadowed by person 1's hand and head. This is evident from the estimated m parameter which was equal to 0.30 (Table I). For UE₁ at person 1's head while walking towards person 2, UE₂ also at the head, a significant variation of the resultant dominant component was also observed as shown in Table I. In this channel both UEs are shadowed by the respective user's hands and heads.

Figs. 3 and 4 show the received signal power and shadowed κ - μ PDF fitted to the empirical probability density respectively for UE₁ at person 1's head while walking away from UE₂ which was in person 2's pocket. In this channel, a shadowed resultant dominant component was also observed to exist (Table I). As we can see from Fig. 4, equation (1) provides a good fit to the measured data, especially at low signal levels.

$$f_r(r) = \frac{2r^{2\mu-1}}{\Gamma(\mu)} \left(\frac{\mu(1+\kappa)}{\hat{r}^2} \right)^\mu \left(\frac{m\hat{r}^2}{\mu(1+\kappa)\Omega + m\hat{r}^2} \right)^m \exp\left(-\frac{\mu(1+\kappa)r^2}{\hat{r}^2} \right) {}_1F_1\left(m; \mu; \frac{\Omega(\mu(1+\kappa)r^2)}{\hat{r}^2(\mu(1+\kappa)\Omega + m\hat{r}^2)} \right) \quad (1)$$

IV. CONCLUSION

This paper has presented some of the initial findings of a channel measurement campaign which has aimed to characterize the indoor D2D communications channel. To this end, the shadowed κ - μ fading PDF has been fitted to a range of measured D2D channels and has been shown to provide a good fit. For some channels, significant shadowing of the resultant dominant component has been observed. Finally the estimated parameters for the log-distance path loss model have also been provided so that the results presented in this paper can be fully reproduced for use in channel simulators.

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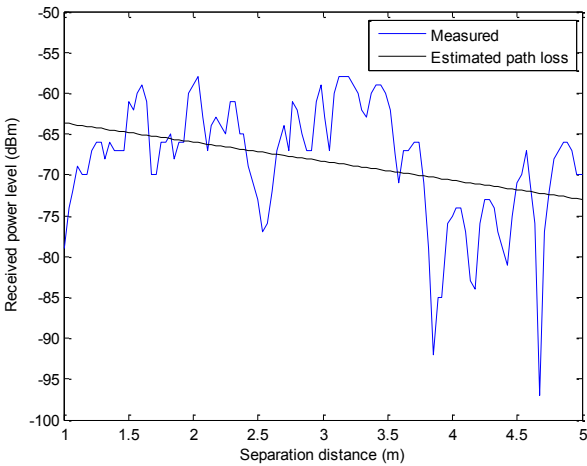


Fig. 1 Received signal power while person 1 (UE₁) walked towards UE₂ positioned on desktop.

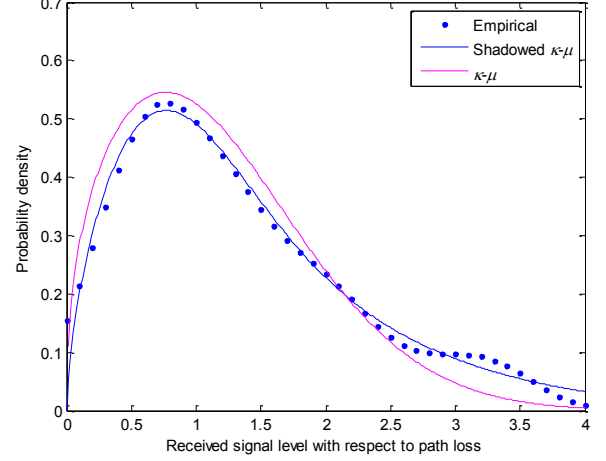


Fig. 2 Empirical and theoretical probability densities for Person 1 (UE₁) walking towards UE₂ positioned on desktop. Also shown for comparison is the κ - μ PDF ($\kappa = 0.01$, $\mu = 0.71$, $\Omega = 1.98$).

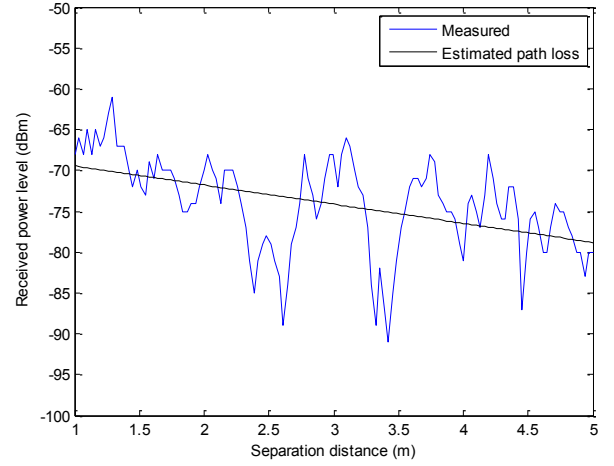


Fig. 3 Received signal power for UE₁ at person 1's head while walking away from UE₂ which was in person 2's pocket.

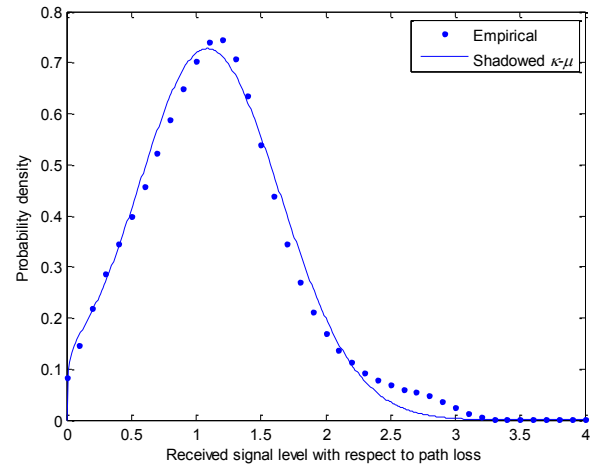


Fig. 4 Empirical and theoretical probability densities for UE₁ at person 1's head while walking away from UE₂ which was in person 2's pocket.

TABLE I. ESTIMATED PARAMETERS FOR ALL D2D CHANNELS

Scenario	Shadow Fading					Path Loss	
	$\hat{\mu}$	$\hat{\kappa}$	\hat{r}	\hat{m}	$\hat{\Omega}$	\hat{n}	$\hat{P}_{dB}(d_0)$
UE ₁ at head walking towards UE ₂ (desktop)	0.80	1.13	1.45	0.30	2.07	-2.34	-61.31
UE ₁ at head walking away from UE ₂ (desktop)	0.60	0.49	1.47	1295	1.33	-1.38	-62.84
UE ₁ at head walking towards UE ₂ (head)	1.09	1.06	1.47	0.33	0.98	-3.42	-58.02
UE ₁ at head walking away from UE ₂ (head)	0.70	5.24	1.36	8937	1.11	-0.11	-60.17
UE ₁ at head walking towards UE ₂ (pocket)	1.32	0.01	1.16	0.08	0.43	-2.99	-63.94
UE ₁ at head walking away from UE ₂ (pocket)	0.61	6.14	1.28	2.58	1.33	-2.34	-67.10